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COMPARISON OF NATURAL BACKGROUND DOSE RATES FOR RESIDENTS OF THE AMARGOSA VALLEY, NV, TO THOSE IN LEADVILLE, CO, AND THE STATES OF COLORADO AND NEVADA

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Abstract – **In the latter half of 2005, the U.S. Environmental Protection Agency (USEPA) published a Proposed Rule (40 CFR Part 197) for establishing a dose rate standard for limiting radionuclide releases from the proposed Yucca Mountain high-level radioactive waste repository during the time period from 10^4 to 10^6 years after closure. The proposed standard was based on the difference in the estimated total dose rate from natural background in the Amargosa Valley and the "average annual background radiation" for the State of Colorado. As defined by the USEPA, "natural background radiation consists of external exposures from cosmic and terrestrial sources, and internal exposures from indoor exposures to naturally-occurring radon." On the basis of its assessments, the USEPA estimated that the difference in the dose rate in the two identified areas was 3.5 mSv y^{-1}. The purpose of this review was to provide an independent evaluation and review of this estimate. One of the first observations was that, because site-specific dose rate measurements for the Amargosa Valley "were not available," the dose rates for various sources of natural background in that area, used by the USEPA in its assessment, were based on modifications of the average values for the State of Nevada. A second observation was that the conversion factor applied in estimating the dose rates due to exposures to indoor radon and its decay products was a factor of 2 higher than the currently accepted value. Further review revealed that site-specific data for many natural background sources in the Amargosa Valley were available. One particularly important observation was that about 91% of the residents of that area live in mobile homes which, due to their construction and design, have indoor radon concentrations comparable to, or less than, those outdoors. For that reason, alone, the USEPA estimate of the average dose rate for residents of the Amargosa Valley, due to indoor radon, was not valid. For purposes of the comparisons in this paper, site-specific dose rates were estimated for all major natural background sources of exposure to residents of the Amargosa Valley, and those in Leadville, CO. The latter community was selected for comparison because of its altitude (3,200 m) and accompanying high cosmic radiation dose rate, and the fact the size of its population is comparable to that of Amargosa Valley. For completeness, similar comparisons of the estimated dose rate in the Amargosa Valley to those for residents of Leadville, CO, the States of Colorado and Nevada. The estimated dose rates in Leadville, the State of Colorado, and the State of Nevada, were higher than those in the Amargosa Valley by 4.09, 2.62, and 1.01 mSv y^{-1}, respectively. Associated uncertainties were**

highest for the estimated dose rates due to exposures to radon and its decay products. The overall uncertainty in the dose estimates, including the errors in the radon dose coefficient, could be as high as 142%.

Key words: Basis for dose rate limits; proposed Yucca Mountain repository; natural background sources; Amargosa Valley, NV; Leadville, CO; uncertainties

INTRODUCTION

On August 22, 2005, the U.S. Environmental Protection Agency (USEPA 2005) published a Proposed Rule (40 CFR Part 197) for establishing a dose rate standard for limiting radionuclide releases from the proposed Yucca Mountain high-level radioactive waste repository during the time period from 10^4 to 10^6 y after closure. Shortly thereafter, the U.S. Nuclear Regulatory Commission (USNRC 2005) published a Proposed Rule (10 CFR Part 63) for implementing the proposed USEPA standard. The dose rate limit was based on the difference in the estimated total dose rate from natural background in the Amargosa Valley, NV, and the "average annual background radiation" for the State of Colorado. In this regard, it should be noted that the use of such comparisons is in accord with recommendations of the International Commission on Radiological Protection (ICRP 1991) as a basis for establishing long-term dose rate limits for members of the public. The goal in preparing the assessments that follow was to provide independently developed, scientifically based, information on estimates of the dose rates from natural background sources in the Amargosa Valley, and three other areas within that portion of the western United States. The objective was neither to support nor to refute the dose rate limit proposed by the USEPA.

In its Proposed Rule, the USEPA (2005) stated that, in making such assessments, natural background radiation "consists of external exposures from cosmic and terrestrial sources, and internal exposures from indoor exposures to naturally-occurring radon." This left open the question, in the cases of cosmic and terrestrial radiation, whether only indoor exposures, outdoor exposures, or a combination of the two, were to be considered. This ambiguity was answered in that the USEPA used as a source for their data a report prepared by Mauro and Briggs (2005) that limited the assessments for all three sources to indoor exposures. The ramifications of these decisions, and other aspects of such an assessment, are among the topics that are addressed in the discussions that follow. To ensure that the review that follows provided a complete range of dose assessments, both outdoor and indoor exposures were evaluated for all three of the stipulated sources of natural background. In addition, rather than following the USEPA approach of limiting the comparison of the dose rates in the Amargosa Valley to the average for the State of Colorado, comparisons are provided between the estimated dose rate for the Amargosa Valley and Leadville, CO, and the State of Nevada, as well as the State of Colorado.

DOSE ESTIMATES FOR NATURAL BACKGROUND

The major contributors to the dose rates from natural background sources are (1) cosmic radiation; (2) terrestrial radiation; (3) radon and its decay products; and (4) radionuclides in the body (as a result of ingestion). For purposes of the assessments that follow, dose estimates for the last source were not included. This was based on the USEPA guidance, as well as the fact that, due to the globalization of the world's food supply, differences in the dose rates from ingested radionuclides in various areas of the United States are minimal. While one might assume that the intake of ^{226}Ra and ^{228}Ra in ground waters consumed by residents in the Amargosa Valley might have significantly increased their dose rates, assessments proved that this was not the case (Moeller et al. 2005). The same was true for Leadville, CO, since their drinking water supply is primarily derived from surface sources.

For purposes of background, the National Council on Radiation Protection and Measurements (NCRP 1987b) has estimated that the average effective dose, per year of intake, to the average member of the U.S. population, due to the ingestion of naturally occurring radionuclides, is 0.41 mSv. Had the dose rate from this source been uniformly applied to residents at all four locations, this addition would have made no difference in the outcome of the comparisons. A similar decision was made relative to the contributions to the indoor dose rates due to external exposures from building materials, such as concrete and brick, the reasons being both that data for estimating the accompanying dose rates were not available, and existing estimates indicated that the average accompanying dose rates were low (about 10 μSv y^{-1} to 30 μSv y^{-1}). For similar reasons, the additional cosmic radiation doses due to commercial airline travel were not included. Also not included were exposures from consumer products, such as tobacco. Based on these considerations, and the limitations imposed by the USEPA definition of natural background, the dose rate estimates that follow are restricted to those from the first three sources listed above, the one difference being that dose rates due to outdoor exposures, as well as indoor exposures, were included.

To ensure comparability, all estimates were expressed in terms of effective doses. In the case for cosmic and terrestrial radiation, the accompanying estimates represented a dose rate (mSv y^{-1}). For inhaled radon and its decay products, the comparable estimates represented, as would have been the case for ingested radionuclides, the effective doses per year of intake. For simplicity, these estimates were also expressed in units of mSv y^{-1}.

Among the dose estimates that follow, the most challenging were those involving the assessments of exposures to radon and its decay products, one of the primary reasons being an ongoing problem in confirming an appropriate dose conversion factor. This has largely been due to an inability to resolve differences in the estimated health effects based on the epidemiological data, and those based on physical-biological dosimetry. Fortunately, due to recent developments, most importantly an increase in the estimated lung cancer risk to uranium miners based on the epidemiological data, there is now good agreement in the two sets of estimates. The currently accepted factor for converting integrated exposures to the corresponding effective dose is 4.8 mSv per Working Level Month (WLM) (Harley 2005‡).

In its comprehensive report on natural background radiation, the United Nations Scientific Committee on the Effects of Ionizing Radiation (UNSCEAR 2000) recommended a dose conversion factor of 9 nSv (Bq h m^{-3})$^{-1}$. The actual estimates ranged from 6 to 15 nSv (Bq h m^{-3})$^{-1}$. To ensure that dose estimates using either the factor based on exposures in WLMs, or the one based on airborne concentrations of radon and its decay products, would provide equivalent dose rate estimates, the UNSCEAR factor was increased to 9.44 nSv (Bq h m^{-3})$^{-1}$. The basis for this derivation is as follows. The ICRP (1993) states that an indoor exposure at home to a concentration of 1 Bq m^{-3} for 7,000 h (which represents an annual occupancy factor of 0.8) would yield an integrated dose of 4.40×10^{-3} WLM. Applying the revised dose conversion factor, 4.8 mSv WLM^{-1}, the comparable dose conversion factor, D, expressed in units of nSv [Bq h m^{-3}]$^{-1}$, would be:

$$(4.8 \text{ mSv WLM}^{-1}) \times (4.40 \times 10^{-3} \text{ WLM [Bq 7000-h m}^{-3}]^{-1})$$

$$= 0.0211 \text{ mSv [Bq 7000-h m}^{-3}]^{-1}.$$

To express this in terms of the effective dose (Bq h m^{-3})$^{-1}$, it must be divided by 7,000. Following this approach, the dose conversion factor (D) would be:

$$0.0211 \text{ mSv [Bq 7000-h m}^{-3}]^{-1} \div 7000$$

$$= 3.02 \times 10^{-6} \text{ mSv [Bq h m}^{-3}]^{-1} = 3.02 \text{ nSv [Bq h m}^{-3}]^{-1}.$$

Converting this into the format for use in the UNSCEAR equation for estimating the accompanying effective dose due to exposures to airborne radon and its decay products, this estimate must be divided by an *indoor* equilibrium factor of 0.4 and occupancy factor of 0.8. This yields a value for the dose conversion factor (D) of:

$$3.02 \text{ nSv [Bq h m}^{-3}]^{-1} \div (0.4 \times 0.8) = 9.44 \text{ nSv [Bq h m}^{-3}]^{-1}.$$

DOSE RATE ESTIMATES FOR THE AMARGOSA VALLEY, NV

For each of the two communities and two states identified above, individual estimates could be made of the dose rates for outdoor and indoor sources of each of the three specified natural background sources.

Cosmic radiation

Outdoors. According to Maheras (1999), the average *outdoor* cosmic ray dose rate in the Amargosa Valley is 0.39 mSv y^{-1}. Prorating this dose rate to account for the fact that the average person spends 20% of his/her time outdoors (UNSCEAR 2000), the estimated average *outdoor* effective dose rate, due to exposures of residents of the Amargosa Valley, would be:

$$(0.39 \text{ mSv y}^{-1}) \times (0.2) = 0.08 \text{ mSv y}^{-1}.$$

Indoors. As was the case for estimating the outdoor dose rates, it will be necessary to adjust the indoor dose rates for an occupancy factor of 0.8. In addition, the dose rate will be reduced to account for the building structural shielding factor. In this case, both the NCRP (1987b), and UNSCEAR (2000), estimate that that the roof of a building and its support structures reduce the cosmic dose rate by 20%. This converts to a shielding factor of 0.8. One additional factor that had to be considered was that surveys had shown that about 91% of the residents of the Amargosa Valley reside in mobile homes (Rautenstrauch et al. 2003). Although some might assume that such a home would provide less shielding than a conventional structure, this is not the case. Manufacturers of mobile homes are required to comply with essentially the same construction requirements. These are stipulated in the Code of National Manufactured Home Construction and Safety Standards, which was promulgated by the U.S. Department of Housing and Urban Development, following passage by the U.S. Congress (1974) of the National Manufactured Housing Construction and Safety Standards Act of 1974. This being the case, the same shielding factor (0.8) recommended for conventional homes was used in assessing the dose rates to people living in mobile homes. Following this approach, the prorated average *indoor* dose rate from cosmic radiation to the Amargosa Valley population, taking into account the occupancy factor (0.8) and a structural shielding factor (0.8), was estimated to be:

$$(0.39 \text{ mSv y}^{-1}) \times (0.8) \times (0.8) = 0.25 \text{ mSv y}^{-1}.$$

Total cosmic radiation dose rate. On this basis, the estimated total (*outdoor* plus *indoor*) effective dose rate from cosmic radiation to the residents of the Amargosa Valley was:

$$(0.08 \text{ mSv y}^{-1}) + (0.25 \text{ mSv y}^{-1}) = 0.33 \text{ mSv y}^{-1}.$$

Terrestrial radiation

The effective dose rate from terrestrial radiation is a direct function of the concentrations of primordial radionuclides in the ground. Such radionuclides are commonly present in igneous rocks, such as granite, as well as in shale and phosphate rocks.

Outdoors. According to Maheras (1999), the average *outdoor* dose rate from terrestrial radiation in the Amargosa Valley is 0.56 mSv y^{-1}. Adjusting this dose rate, to account for an outdoor *occupancy* factor of 0.2, yields a prorated *outdoor* terrestrial dose rate of:

$$(0.56 \text{ mSv y}^{-1}) \times (0.2) = 0.11 \text{ mSv y}^{-1}.$$

Indoors. As was the case for cosmic radiation, the *outdoor* dose rate must be adjusted to account for a building shielding factor of 0.8 (UNSCEAR 2000; NCRP 1987b), and for an estimated indoor occupancy factor of 0.8. This yields an average prorated *indoor* dose rate from this source of:

$$(0.56 \text{ mSv y}^{-1}) \times (0.8) \times (0.8) = 0.36 \text{ mSv y}^{-1}.$$

Total terrestrial dose rate. On this basis, the estimated total (*outdoor* plus *indoor*) effective dose rate to residents of the Amargosa Valley due to exposures to terrestrial radiation would be:

$$(0.11 \text{ mSv y}^{-1}) + (0.36 \text{ mSv y}^{-1}) = 0.47 \text{ mSv y}^{-1}.$$

Radon and its decay products

Outdoors. According to Maheras (1999), measurements made from 1991 to 1995 yielded average *outdoor* radon concentrations of 0.32 pCi L^{-1} at the near-field stations (i.e., at Yucca Mountain), and 0.34 pCi L^{-1} (12.6 Bq m^{-3}) for off-site areas (i.e., Amargosa Valley). Based on an assumed radon decay product equilibrium factor of 0.6 (UNSCEAR 2000), an outdoor occupancy factor of 0.2 (i.e., 1,760 h y^{-1}), and applying the UNSCEAR dose conversion factor, as modified above, the estimated outdoor dose rate due to airborne radon and its decay products would be:

$$(12.6 \text{ Bq m}^{-3}) \times (0.6) \times (1760 \text{ h y}^{-1}) \times (9.44 \text{ nSv [Bq h m}^{-3}]^{-1})$$

$$= 1.3 \times 10^{5} \text{ nSv y}^{-1} = 0.13 \text{ mSv y}^{-1}.$$

Indoors. As previously noted, surveys showed that about 91% of the Amargosa Valley residents live in mobile homes. According to staff members in the Florida and North Carolina State Radiation Control Programs, and the USEPA, the average *indoor* radon concentration, for this population group, would be essentially the same as that outdoors, namely, 12.6 Bq m^{-3}. The reason is that mobile homes are typically placed on supports such that the floor is a 0.3 m (1 ft) or more above the ground. As a result, there is a relatively small (if any) pressure gradient to "force" the radon, released from the ground, to move into the home. In addition, the supporting structures for such homes include several layers of plywood, that are covered by floors that, not only have no open cracks or joints but also are, in turn, supported by a steel box frame enclosed within an impervious outer steel sheet metal container.

This will not be the case, however, for the 9% of the Amargosa Valley residents who live in conventional homes. For them, an estimate of the average indoor radon concentration is needed. What proved to be an ideal source was the database maintained on a county-by-county basis by the Lawrence Berkeley National Laboratory (LBNL 2005). For Nye County, NV, in which the Amargosa Valley is located, the reported arithmetic mean was 1.25 ± 0.19 pCi L^{-1} (46.2 ± 6.9 Bq m^{-3}). The coefficient of variance (CV) was 15%. Prorated on the basis of the relative percentages of the Amargosa population residing in the mobile and conventional homes in the Amargosa Valley, the average *indoor* radon concentration in these homes would be:

$$(12.6 \text{ Bq m}^{-3}) \times (0.91) + (46.2 \text{ Bq m}^{-3}) \times (0.09)$$

$$= (11.5 \text{ Bq m}^{-3}) + (4.2 \text{ Bq m}^{-3}) = 15.7 \text{ Bq m}^{-3}.$$

For indoor conditions, the UNSCEAR conversion factor is based on an assumed average breathing rate of 0.6 m^3 h^{-1}, an aerosol median diameter of 100-150 nm, an unattached fraction of 0.05, and an *indoor* occupancy factor of 0.8 (i.e., 7,000 h y^{-1}). The equilibrium factor for radon decay products inside both the mobile and conventional homes was assumed to be 0.4 (UNSCEAR 2000). The basis for the lower indoor equilibrium factor is the presence of surfaces with which the electrically charged decay products can readily come into contact. Once they do so, they adhere to these surfaces and are no longer available for inhalation. On this basis, the estimated average *indoor* effective dose rate to residents of the Amargosa Valley would be:

$$(15.7 \text{ Bq m}^{-3}) \times (0.4) \times (7000 \text{ h y}^{-1}) \times (9.44 \text{ nSv [Bq h m}^{-3}]^{-1})$$

$$= 4.1 \times 10^5 \text{ nSv y}^{-1} = 0.41 \text{ mSv y}^{-1}.$$

Total radon dose rate. Adding the outdoor and indoor estimates, the total estimated average combined effective dose rate to residents of the Amargosa Valley, NV, due to exposures to radon and its decay products, would be:

$$(0.13 \text{ mSv y}^{-1}) + (0.41 \text{ mSv y}^{-1}) = 0.54 \text{ mSv y}^{-1}.$$

In addition to ^{222}Rn (radon), residents in the Amargosa Valley, as well as those in the other areas for which dose rate estimates are being made, will be subjected to the inhalation of naturally occurring ^{220}Rn ("thoron") and its decay products. Assessments of the dose rates from this radionuclide are difficult for a variety of reasons. One is that its half-life is short (< 1 minute), which makes it difficult to measure the associated equilibrium factor. Another is that several investigators have reported that upwards of 25% of the concentrations of ^{222}Rn, as measured using conventional techniques, may be due to ^{220}Ra, and that as much as 20% of the estimated dose rates from ^{222}Rn may be similarly due to ^{220}Rn (NCRP 1984). Exacerbating the situation is that there are no epidemiological data for quantifying the lung cancer risk due to the inhalation of ^{220}Rn, an essential factor for deriving a dose conversion factor (UNSCEAR 2000). If that were not enough, data on its concentrations in outdoor and indoor air in the U.S. are extremely limited, particularly in the four areas being evaluated in this assessment. For this reason, estimates of the dose rates from ^{220}Rn are not included in any of these assessments.

Total natural background dose rate, Amargosa Valley

Summarized in Table 1 are the estimated dose rates to residents of the Amargosa Valley, NV, due to exposures to natural background sources of cosmic and terrestrial radiation, plus radon and its decay products. As will be noted, the total estimated dose rate was 1.34 mSv y^{-1}.

Table 1. Estimated average natural background dose rates to residents of the Amargosa Valley, NV.

Natural background source	Effective dose rate (mSv y^{-1})
Cosmic radiation	
(outdoors)	0.08
(indoors)	0.25
Terrestrial radiation	
(outdoors)	0.11
(indoors)	0.36
Radon decay products	
(outdoors)	0.13
(indoors)	0.41
Total	1.34

DOSE RATE ESTIMATES FOR LEADVILLE, CO

Cosmic radiation

Outdoors. The average *outdoor* dose rate from cosmic radiation in Leadville, CO, was estimated to be 1.25 mSv y^{-1} (NCRP, 1987b). Applying an occupancy factor of 0.2, the prorated average *outdoor* dose rate would be:

$$(1.25 \text{ mSv y}^{-1}) \times (0.2) = 0.25 \text{ mSv y}^{-1}.$$

Indoors. Because snow cover on the roofs of the homes will reduce the dose rate during the winter months, the dose rates for summer and winter were estimated separately. Assuming that summer and winter have durations of 6 months (Leadville, CO, Profile 2006), each was assigned an occupancy factor of 0.4. Following this approach, and assigning a structural reduction factor of 0.8, the prorated indoor dose rate for the *summer* would be:

$$(1.25 \text{ mSv y}^{-1}) \times (0.8) \times (0.4) = 0.40 \text{ mSv y}^{-1}.$$

In estimating the prorated winter dose rate, the 1.25 mSv y^{-1} *outdoor* dose rate will need to be reduced not only to account for a structural shielding factor of 0.8, but also to account for the shielding effect of snow cover on the roofs of the houses. Based on information presented in its website (Leadville, CO, Profile 2006), the ground snow cover in Leadville during the winter ranges up to three to four feet (90 to 120 cm). For purposes of the dose rate estimates that follow, it will be assumed that the average roof snow cover during winter (which will be conservatively assumed to last six months) is 50 cm. According to UNSCEAR (2000), ground snow cover reduces the *terrestrial* dose rate by about 1% per centimeter depth, assuming a snow density of 0.1. For purposes of this assessment, it will be conservatively assumed that this same factor can be applied to estimate the reduction in the indoor dose rate from *cosmic* radiation in Leadville. In this context, the term, conservative, means that these assumptions will ensure that the indoor cosmic radiation dose rate for Leadville will not be over-estimated, and thereby lead to a higher difference than justified in the dose rate estimates for residents in that city compared to those in the Amargosa Valley.

Under these assumptions, a roof snow depth of 50 cm would reduce the incoming cosmic radiation by 50%. This reduction, combined with a structural shielding factor of 0.8, and a winter occupancy factor of 0.4, yields an *indoor* cosmic radiation dose rate during the six *winter* months of:

$$(1.25 \text{ mSv y}^{-1}) \times (0.5) \times (0.8) \times (0.4) = 0.20 \text{ mSv y}^{-1}.$$

This yields a prorated total *indoor* summer plus winter cosmic radiation dose rate of:

$$(0.40 \text{ mSv y}^{-1}) + (0.20 \text{ mSv y}^{-1}) = 0.60 \text{ mSv y}^{-1}.$$

Total cosmic radiation dose rate. Combining the *outdoor* and *indoor* prorated cosmic dose rate estimates yields a total dose rate of:

$$(0.25 \text{ mSv y}^{-1}) + (0.60 \text{ mSv y}^{-1}) = 0.85 \text{ mSv y}^{-1}.$$

Terrestrial radiation

Outdoors. Stone et al. (1999) have conducted extensive surveys of the total absorbed dose rates due to the ionizing components from cosmic and terrestrial radiation sources at multiple locations in the State of Colorado. For communities located more than 2,000 m above sea level – Leadville is located 3,200 m above sea level (NCRP 1987b) – they estimated that the total average absorbed dose rate from these two sources was 196 nGy h^{-1}. Applying a radiation weighting factor of unity (i.e., 1 Sv Gy^{-1}), this is equivalent to 196 ± 33 nSv h^{-1}. For communities east of the Continental Divide, where Leadville is located, analyses showed that the terrestrial sources contributed an average of about two-thirds of the total; that is to say, the terrestrial absorbed dose rate was about twice that from cosmic radiation. Stone et al. also observed a linear relationship between the terrestrial dose rates and elevation, although the relationship was weak. Adopting a conservative approach, as defined above, it will be assumed that two-thirds of the total absorbed dose rate from the ionizing components of cosmic and terrestrial radiation in Leadville was due to terrestrial sources. Applying a radiation weighting factor of unity, the corresponding estimated *outdoor* effective dose rate from terrestrial radiation (assuming continuous year-round exposure, and that the Stone et al. mean value for communities above 2,000 m applies) would be:

$$(196 \text{ nSv h}^{-1}) \text{ x } (8760 \text{ h y}^{-1}) \text{ x } (0.67) = 1.15 \text{ mSv y}^{-1}.$$

This compares to an estimated average terrestrial dose rate for the State of Colorado of 1.17 mSv y^{-1}, and to a mean dose rate of about 12.3 μrem h^{-1} (1.08 mSv y^{-1}) for the Rocky Flats—Denver area (Oakley 1972). Another "bench-mark" for the State of Colorado is an average terrestrial dose rate estimate of 0.90 mSv y^{-1} (range: 0.75 to 1.40 mSv y^{-1}) for the Colorado Plateau, which encompasses about 35% of the State of Colorado (NRC 1980). A closer examination of the 196 nGy h^{-1} average estimate, for locations above 2,000 m, shows that all except one was at an elevation of 2,800 m or less, compared to 3,200 m for Leadville. For purposes of these analyses, it will be assumed that the terrestrial dose rate in Leadville was equal to:

$$1.20 \text{ mSv y}^{-1}.$$

This is slightly above the average for the State of Colorado, as reported by Oakley (1972).

In contrast to the approach applied in accounting for snow cover on the roofs of homes (in estimating the *indoor* effective dose rate from cosmic radiation), one might assume that the *outdoor* effective dose rate, due to terrestrial radiation during the winter, would not need to be reduced since it is "common" practice to remove the snow cover from paths and walkways. It has been reported, however, that multiple residents of Leadville wear snowshoes and walk on top of the snow. Since data are not available for confirming either assumption, or the relative distribution of the population involved in each practice, the approach adopted in estimating the winter terrestrial dose rate was to assume that:

- The average winter ground snow cover is about 60 cm (2 ft). This is based on the reported peak depth of 90 to 120 cm (Leadville, CO, Profile 2006).
- Half (50%) of the people walk on top of the snow. Based on the previously cited reduction of about 1% per centimeter depth (UNSCEAR 2000), this means that the dose rate will be reduced by 60%, yielding a dose reduction factor of 0.4.
- Half of the people walk on pathways and sidewalks from which the snow has been removed. For them, it will be assumed that there is no reduction in the terrestrial dose rate. While it might appear that the shielding effect of moisture and ice, remaining in or on the soil in areas that had been cleared, would reduce the terrestrial dose rates, the accompanying restrictions on the release of radon and its decay products from the ground more than offset the potential shielding benefits of the moisture and ice (Oakley 1972; NCRP 1987b).
- For purposes of the dose rate estimates, the total *outdoor* occupancy factor of 0.2 will be separated into two parts. That is, an occupancy factor of 0.1 will be applied in estimating the dose rates for the winter months and the same factor will be applied in estimating the dose rates for the summer months.

On this basis, the prorated outdoor dose rate for the 50% of the people who walk on top of the ground snow cover would be:

$$(1.20 \text{ mSv y}^{-1}) \times (0.5) \times (0.4) \times (0.1) = 0.02 \text{ mSv y}^{-1}.$$

The prorated dose rate for the 50% of the people who walk on sidewalks and pathways, from which the snow cover has been removed, would be:

$$(1.20 \text{ mSv y}^{-1}) \times (0.5) \times (0.1) = 0.06 \text{ mSv y}^{-1}.$$

This yields a total average prorated *winter* terrestrial dose rate of:

$$(0.02 \text{ mSv y}^{-1}) + (0.06 \text{ mSv y}^{-1}) = 0.08 \text{ mSv y}^{-1}.$$

Based on the information provided above, the average outdoor terrestrial dose rate during the *summer* months, applying an occupancy factor of 0.1, would be:

$$(1.20 \text{ mSv y}^{-1}) \times (0.1) = 0.12 \text{ mSv y}^{-1}.$$

Total outdoor dose rate. Based on the above estimates, the total prorated average *outdoor* terrestrial dose rate to the residents of Leadville, CO, would be:

$$(0.08 \text{ mSv y}^{-1}) + (0.12 \text{ mSv y}^{-1}) = 0.20 \text{ mSv y}^{-1}.$$

In reality, accounting for the winter ground snow cover made little difference in the total dose rate. Had there been no winter snow, the estimated total dose rate would have been 0.24 mSv y^{-1}. This is largely due to the relatively low outdoor occupancy factor of 0.2. Although the estimated amount of ground snow cover has associated uncertainties, the impact on the dose estimates proved to be negligible.

Indoors. The indoor terrestrial dose rate will not be affected by the ground snow cover. Estimating it will require only the modification of the outdoor dose rate through the application of a structural shielding factor of 0.8, and an occupancy factor of 0.8. Following this approach, the estimated *indoor* dose rate from this source would be:

$$(1.20 \text{ mSv y}^{-1}) \times (0.8) \times (0.8) = 0.77 \text{ mSv y}^{-1}.$$

Total terrestrial dose rate. This yields a total estimated *outdoor* plus *indoor* terrestrial dose rate for Leadville of:

$$(0.20 \text{ mSv y}^{-1}) + (0.77 \text{ mSv y}^{-1}) = 0.97 \text{ mSv y}^{-1}.$$

Radon decay products

Outdoors. In a detailed study conducted over a three-year period, the mean outdoor ^{222}Rn concentration in Fort Collins, CO, was determined to be 18 ± 10 Bq m^{-3} (Borak and Baynes 1999). The CV was 56%. Measurements showed that the terrestrial absorbed dose rate in this same city was 75 nGy h^{-1} (Stone et al. 1999). As indicated earlier, the comparable terrestrial effective dose rate in Leadville was estimated to be two thirds of 196 nGy h^{-1}, or 131 nGy h^{-1}, which is a factor of 1.75 higher than that for Fort Collins. Assuming that there is a direct relationship between the terrestrial dose rate and the outdoor concentration of ^{222}Rn, and that the geology of Fort Collins and Leadville are similar, this would yield an estimated outdoor concentration of radon in Leadville of:

$$(18 \text{ Bq m}^{-3}) \times (1.75) = 31.5 \text{ Bq m}^{-3}.$$

Based on an *outdoor* radon decay product equilibrium factor of 0.6, assuming an *outdoor summer* occupancy factor of 0.1 (880 h y^{-1}), and applying the conversion factor (D), yields an estimated *outdoor summer* effective dose rate of:

$$(31.5 \text{ Bq m}^{-3}) \times (0.6) \times (880 \text{ h y}^{-1}) \times (9.44 \text{ nSv [Bq h m}^{-3}]^{-1})$$

$$= 0.16 \times 10^6 \text{ nSv y}^{-1} = 0.16 \text{ mSv y}^{-1}.$$

As was the case for assessing the terrestrial dose rates, a separate estimate must be made for the winter months when the ground will be covered by snow. Adopting a conservative approach, as previously define, it will be assumed that the snow cover is 100% effective in restricting the release of ^{222}Rn from localized sources during the winter months. Nonetheless, winter weather patterns will undoubtedly bring atmospheric radon from other areas into Leadville. For that reason, it will be assumed that the outdoor radon concentration during the winter will be equal to the average concentration of radon in the air (8 Bq m^{-3}) over the continents in the northern hemisphere (NCRP 1987b). Following the same approach that was used in estimating the dose rate during the summer months, the estimated contribution of *outdoor* radon and its decay products to the effective dose rate to residents of Leadville during the winter months would be:

$$(8 \text{ Bq m}^{-3}) \times (0.6) \times (880 \text{ h y}^{-1}) \times (9.44 \text{ nSv [Bq h m}^{-3}]^{-1})$$

$$= 0.04 \times 10^6 \text{ nSv y}^{-1} = 0.04 \text{ mSv y}^{-1}.$$

Combining the estimated summer and winter dose rates from outdoor exposures to radon and its decay products, the estimated total *outdoor* effective dose rate from this source is:

$$(0.16 \text{ mSv y}^{-1}) + (0.04 \text{ mSv y}^{-1}) = 0.20 \text{ mSv y}^{-1}.$$

Indoors. The Lawrence Berkeley National Laboratory High-Radon Project provides for Lake County, CO, in which Leadville is located, an estimated arithmetic mean *indoor* radon concentration of 3.49 ± 1.01 pCi L^{-1} (129 ± 37 Bq m^{-3}) (LBNL 2005). The CV was 29%. Applying the dose conversion factor (D), and a radon decay product equilibrium factor of 0.4, the estimated average *indoor* dose rate from this source, prorated to account for an occupancy factor of 0.8 (7,000 h y^{-1}), would be:

$$(129 \text{ Bq m}^{-3}) \times (0.4) \times (7000 \text{ h y}^{-1}) \times (9.44 \text{ nSv [Bq h m}^{-3}]^{-1})$$

$$= 3.41 \times 10^6 \text{ nSv y}^{-1} = 3.41 \text{ mSv y}^{-1}.$$

Total radon dose rate. Adding the above two estimates, the total average combined *outdoor* and *indoor* effective dose rate to residents of Leadville, CO, due to exposures to radon and its decay products, would be:

$$(0.20 \text{ mSv y}^{-1}) + (3.41 \text{ mSv y}^{-1}) = 3.61 \text{ mSv y}^{-1}.$$

Total natural background dose rate, Leadville, CO

Summarized in Table 2 are the estimated dose rates to residents of Leadville, CO, due to due to exposures to natural background sources of cosmic and terrestrial radiation, plus radon and its decay products. As will be noted, the total estimated dose rate due to such exposures was 5.43 mSv y^{-1}.

Table 2. Estimated average natural background dose rates to residents of Leadville, CO.

Natural background source	Effective dose rate (mSv y^{-1})
Cosmic radiation	
(outdoors)	0.25
(indoors)	0.60
Terrestrial radiation	
(outdoors)	0.20
(indoors)	0.77
Radon decay products	
(outdoors)	0.20
(indoors)	3.41
Total	5.43

DOSE RATE ESTIMATES FOR THE STATE OF COLORADO

While the review and evaluation presented above is informative, some may question the selection of Leadville, CO, as the community for which the natural background dose rate in the Amargosa Valley, NV, should be compared. Since another choice might have been to use the average total dose rate for the State of Colorado, the comparable dose rates for each of the three specified sources of natural background radiation will be estimated, using the same methodologies as shown above.

Cosmic radiation

Outdoors. The average cosmic radiation dose rate for the State of Colorado, as reported in the report by Mauro and Briggs (2005), was 0.475 mSv y^{-1}. Since this was an estimate for indoors, the building structural shielding factor of 0.8 had already been incorporated. On this basis, the corresponding outdoor dose rate would have been:

$$(0.475 \text{ mSv y}^{-1}) \div (0.8) = 0.59 \text{ mSv y}^{-1}$$

Applying an occupancy factor of 0.2, this yielded a prorated *outdoor* contribution to the cosmic dose rate of:

$$(0.59 \text{ mSv y}^{-1}) \times (0.2) = 0.12 \text{ mSv y}^{-1}$$

Indoors. As noted above, the indoor cosmic radiation dose rate for the State of Colorado, modified to include the building structural shielding factor of 0.8, was 0.475 mSv y^{-1}. Applying an occupancy factor of 0.8, this yields a prorated *indoor* contribution to the cosmic dose rate in the State of Colorado of:

$$(0.475 \text{ mSv y}^{-1}) \times (0.8) = 0.38 \text{ mSv y}^{-1}$$

Since definitive data were not available, the impact of winter snow cover on the roofs of houses in Colorado was not taken into account. This appears to be justified inasmuch as, in most populated areas within the United States, there is little snowfall and it does not remain for long periods of time (Oakley 1972). Even so, based on the definition presented earlier, this represents a source of non-conservatism in the estimated differences between the average natural background dose rates for the State of Colorado and those for the Amargosa Valley, that is, the estimates for Colorado may have been somewhat lower if snow roof cover had been taken into account.

Total cosmic radiation dose rate. Combining the *outdoor* and *indoor* estimates yields an average cosmic dose rate for the State of Colorado of:

$$(0.12 \text{ mSv y}^{-1}) + (0.38 \text{ mSv y}^{-1}) = 0.50 \text{ mSv y}^{-1}$$

Terrestrial radiation

Outdoors. Based on the data in the Mauro and Briggs (2005) report, the terrestrial dose rate, incorporating a structural shielding factor of 0.8, was 0.462 mSv y^{-1}. Adjusting this value to compensate for this reduction, the estimated *outdoor* terrestrial dose rate would have been:

$$(0.426 \text{ mSv y}^{-1}) \div (0.8) = 0.53 \text{ mSv y}^{-1}.$$

Applying an occupancy factor of 0.2, this yields an estimated *outdoor* prorated terrestrial dose rate of:

$$(0.53 \text{ mSv y}^{-1}) \times (0.2) = 0.11 \text{ mSv y}^{-1}$$

As in the comparable case for evaluating the effects of roof snow cover on the dose rates from cosmic radiation, it was not possible to evaluate the potential impacts on the outdoor terrestrial dose rate estimates due to ground snow cover. To the extent that this may have reduced the dose rate estimate, this represents a source of non-conservatism.

Indoors. Application of an occupancy factor of 0.8, and a structural shielding factor of 0.8, to the outdoor dose rate, estimated above, yields an estimated indoor terrestrial dose rate of:

$$(0.53 \text{ mSv y}^{-1}) \times (0.8) \times (0.8) = 0.34 \text{ mSv y}^{-1}$$

Total terrestrial dose rate. On this basis, the total terrestrial effective dose rate would be:

$$(0.11 \text{ mSv y}^{-1}) + (0.34 \text{ mSv y}^{-1}) = 0.45 \text{ mSv y}^{-1}$$

Radon and its decay products

Outdoors. Since the data were not available, it was assumed that the average *outdoor* radon concentration in the State of Colorado was the same as that in Fort Collins (18 ± 10 Bq m^{-3}) (Borak and Baynes 1999). Applying an equilibrium factor of 0.6, and an outdoor occupancy factor of 0.2 (1,760 h), the estimated effective dose rate would be:

$$(18 \text{ Bq m}^{-3}) \times (0.6) \times (1760 \text{ h y}^{-1}) \times (9.44 \text{ nSv } [\text{Bq h m}^{-3}]^{-1})$$

$$= 0.18 \times 10^{6} \text{ nSv y}^{-1} = 0.18 \text{ mSv y}^{-1}.$$

Indoors. Based on the LBNL (2005) database, the average indoor concentration of radon in homes in the State of Colorado is 2.89 ± 2.16 pCi L^{-1} (107 ± 80 Bq m^{-3}). The CV was 75%. Applying the modified UNSCEAR dose conversion factor, assuming an indoor radon decay product equilibrium factor of 0.4, and incorporating the indoor occupancy factor of 0.8 (7,000 h), yields an estimated *indoor* effective dose rate of:

$$(107 \text{ Bq m}^{-3}) \times (0.4) \times (7000 \text{ h y}^{-1}) \times (9.44 \text{ nSv } [\text{Bq h m}^{-3}]^{-1})$$

$$= 2.83 \times 10^{6} \text{ nSv y}^{-1} = 2.83 \text{ mSv y}^{-1}.$$

Total radon dose rate. On this basis, the average combined *outdoor* and *indoor* dose rate due to the inhalation of radon decay products in the State of Colorado would be:

$$(0.18 \text{ mSv y}^{-1}) + (2.83 \text{ mSv y}^{-1}) = 3.01 \text{ mSv y}^{-1}$$

Total natural background dose rate, State of Colorado

Summarized in Table 3 are the estimated dose rates to residents of the State of Colorado, due to exposures to natural background sources of cosmic and terrestrial radiation, plus radon and its decay products. As will be noted, the total estimated dose rate was 3.96 mSv y^{-1}.

Table 3. Estimated average natural background dose rates to residents of the State of Colorado.

Natural background source	Effective dose rate (mSv y^{-1})
Cosmic radiation	
(outdoors)	0.12
(indoors)	0.38
Terrestrial radiation	
(outdoors)	0.11
(indoors)	0.34
Radon decay products	
(outdoors)	0.18
(indoors)	2.83
Total	3.96

DOSE RATE ESTIMATES FOR THE STATE OF NEVADA

Another choice that might have been used for purposes of a comparison is the State of Nevada. Following the same methodologies as applied above, the comparable dose rates are presented below.

Cosmic radiation

Outdoors. The average cosmic radiation dose rate for the State of Nevada, as reported by Mauro and Briggs (2005), was 0.37 mSv y^{-1}. Since, as for the State of Colorado, the building structural shielding factor of 0.8 had already been incorporated into this estimate, the corresponding outdoor dose rate would have been:

$$(0.37 \text{ mSv y}^{-1}) \div (0.8) = 0.46 \text{ mSv y}^{-1}$$

Applying an occupancy factor of 0.2, this yielded a prorated *outdoor* contribution to the cosmic dose rate of:

$$(0.46 \text{ mSv y}^{-1}) \text{ x } (0.2) = 0.09 \text{ mSv y}^{-1}$$

Indoors. Applying an occupancy factor of 0.8 to the indoor structural shielding adjusted dose rate of 0.37 mSv y^{-1} yields a prorated average *indoor* contribution to the cosmic dose rate for the State of Nevada of:

$$(0.37 \text{ mSv y}^{-1}) \times (0.8) = 0.30 \text{ mSv y}^{-1}$$

Total cosmic radiation dose rate. Combining the *outdoor* and *indoor* estimates yields an average cosmic dose rate for the State of Nevada of:

$$(0.09 \text{ mSv y}^{-1}) + (0.30 \text{ mSv y}^{-1}) = 0.39 \text{ mSv y}^{-1}$$

Terrestrial radiation

Outdoors. As in the assessments of the dose rates from cosmic radiation, the terrestrial dose rate was obtained from the report Mauro and Briggs (2005), in which the terrestrial dose rate (0.21 mSv y^{-1}) had similarly been reduced to account for a building shielding factor reduction of 0.8. Adjusting the estimated indoor terrestrial dose rate to compensate for this reduction, the *outdoor* terrestrial dose rate would be:

$$(0.21 \text{ mSv y}^{-1}) \div (0.8) = 0.26 \text{ mSv y}^{-1}.$$

Applying an occupancy factor of 0.2, this yields an estimated *outdoor* prorated terrestrial dose rate of:

$$(0.26 \text{ mSv y}^{-1}) \times (0.2) = 0.05 \text{ mSv y}^{-1}$$

Indoors. Applying an occupancy factor of 0.8 to the indoor structural shielding adjusted dose rate of 0.21 mSv y^{-1} yields a prorated average *indoor* contribution to the terrestrial dose rate of:

$$(0.21 \text{ mSv y}^{-1}) \times (0.8) = 0.17 \text{ mSv y}^{-1}$$

Total terrestrial dose rate. On this basis, the total estimated terrestrial effective dose rate would be:

$$(0.05 \text{ mSv y}^{-1}) + (0.17 \text{ mSv y}^{-1}) = 0.22 \text{ mSv y}^{-1}$$

Radon and its decay products

Outdoors. Since the data were not available, it was assumed that the average *outdoor* radon concentration in the State of Nevada was the same as that in the Amargosa Valley (12.6 Bq m^{-3}). Applying a radon decay product equilibrium factor of 0.6, and an outdoor occupancy factor of 0.2 (1,760 h), the estimated prorated effective dose rate would be:

$$(12.6 \text{ Bq m}^{-3}) \times (0.6) \times (1760 \text{ h y}^{-1}) \times (9.44 \text{ nSv [Bq h m}^{-3}]^{-1})$$

$$= 1.3 \times 10^5 \text{ nSv y}^{-1} = 0.13 \text{ mSv y}^{-1}.$$

Indoors. Based on the LBNL (2005) database, the average indoor concentration of radon in homes in the State of Nevada is 1.65 ± 0.87 pCi L^{-1} (61.1 ± 32.4 Bq m^{-3}). The CV was 53%. Applying the dose conversion factor (D), assuming an indoor radon decay product equilibrium factor of 0.4, and incorporating the indoor occupancy factor of 0.8 (7,000 h), yields an estimated *indoor* effective dose rate of:

$$(61.1 \text{ Bq m}^{-3}) \times (0.4) \times (7000 \text{ h y}^{-1}) \times (9.44 \text{ nSv [Bq h m}^{-3}]^{-1})$$

$$= 1.61 \times 10^6 \text{ nSv y}^{-1} = 1.61 \text{ mSv y}^{-1}.$$

Total radon dose rate. On this basis, the estimated average combined *outdoor* and *indoor* dose rate due to the inhalation of radon and its decay products in the State of Nevada would be:

$$(0.13 \text{ mSv y}^{-1}) + (1.61 \text{ mSv y}^{-1}) = 1.74 \text{ mSv y}^{-1}$$

Total natural background dose rate, State of Nevada

Summarized in Table 4 are the estimated dose rates to residents of the State of Nevada, due to exposures to natural background sources of cosmic and terrestrial radiation, plus radon and its decay products. As will be noted, the total estimated dose rate was 2.35 mSv y^{-1}.

Table 4. Estimated average natural background dose rates to residents of the State of Nevada.

Natural background source	Effective dose rate (mSv y^{-1})
Cosmic radiation	
(outdoors)	0.09
(indoors)	0.30
Terrestrial radiation	
(outdoors)	0.05
(indoors)	0.17
Radon decay products	
(outdoors)	0.13
(indoors)	1.61

Total	2.35

COMPARISON OF ESTIMATED DOSE RATES

For purposes of comparison, the average total dose rates from the major sources of natural background radiation for residents of the Amargosa Valley, NV, were compared to similar estimates for residents of Leadville, CO, and those of the States of Colorado and Nevada. The selection of Leadville was based on the fact that it is located at an elevation of 3,200 m (~10,500 ft) above sea level and has an average outdoor cosmic dose rate of 1.25 mSv y^{-1} (NCRP 1987b). It also is located in an area of relatively high concentrations of naturally occurring radionuclides in the soil, and its population (~2,800) is roughly comparable to that (~1,150) of the Amargosa Valley. Even more important, the availability of site-specific data on many of the factors necessary for estimating natural background dose rates, in the case for both the Amargosa Valley and Leadville, significantly reduced the uncertainties associated with the accompanying dose rate estimates.

The estimated total dose rates from background sources in the Amargosa Valley, Leadville, CO, and the States of Colorado and Nevada, are summarized in Table 5. Based on this information, the total estimated average dose rate in Leadville, CO, was 4.09 mSv y^{-1} higher than that for the Amargosa Valley. In the case of the State of Colorado, it was 2.62 mSv y^{-1} higher, and for the State of Nevada, it was 1.01 mSv y^{-1} higher. The primary source of the relatively large magnitudes of these differences was the significant reduction in the indoor radon exposures to residents of the Amargosa Valley who live in mobile homes. The primary reason that the analyses conducted by the USEPA (2005) showed a difference of 3.5 mSv y^{-1} for the State of Colorado, as compared to the Amargosa Valley, was that the dose conversion factor for radon that was applied was too high.

UNCERTAINTIES

Although dose rates from natural background have been a source of study and evaluation for many years, there continue to be multiple uncertainties in the associated dose rate estimates. According to the UNSCEAR (2000), the major uncertainties in the case of the radon dose assessments are primarily due to the challenges associated with the required dosimetry. In contrast, the major uncertainties for cosmic and terrestrial dose rate assessments are primarily due to a lack of survey data. This is exemplified, in the case of cosmic radiation, by the need for more information on exposures to neutrons at all altitudes and latitudes, and especially to high-energy neutrons and high-Z nuclei at relatively high altitudes. Such information is essential for estimating the dose rates and potential health effects of exposures from this source not only for residents of communities, such as Leadville, CO, but also for the increasing numbers of members of the public, as well as flight attendants and pilots, who fly in commercial passenger aircraft and, most especially, the astronauts who participate in space missions.

Factors for estimating the equivalent doses, based on absorbed dose measurements, require knowledge of the errors associated with the input factors used in developing the radiation weighting factors. Since these are subject to change, as new scientific knowledge becomes available, they represent a continuing, and changing, source of uncertainty. Other, perhaps more mundane, but nonetheless important, sources of uncertainty include the assumptions applied in developing outdoor and indoor occupancy factors, and the structural shielding factors for cosmic and terrestrial radiation. Evaluations show that errors in the values of the outdoor and indoor occupancy factors are not significant contributors in terms of the total uncertainty. Of the sources evaluated in this paper, the estimated dose rates due to exposures to radon and its decay products have the highest uncertainty; those due to exposures to terrestrial exposures have the lowest uncertainty.

In the sections that follow, information will be presented on the uncertainties associated with each of the three natural background sources discussed in this paper. The uncertainties, as presented, include one standard deviation (SD), and/or the coefficient of variance (CV).

Cosmic radiation

Both the composition and intensity of the cosmic-radiation field within the atmosphere of the earth vary markedly. Due to the shielding effects of the atmosphere, the dose rates from this source increase with altitude. Due to the similar effects of the Van Allen belts and the influence of the magnetic field, the dose rates due to the *particle* component also increase with latitude. Taking these and other factors into consideration, Oakley (1972) and Bouville and Lowder (1988) have developed equations for estimating the dose rates from cosmic radiation as a function of altitude. Based on derivatives of the Oakley equation, the accompanying CVs are estimated to range from 9% to 10%; similar assessments of the Bouville and Lowder equation yielded CV estimates ranging from 6% to 11%.

More detailed analyses showed that the CVs for the *charged particle* component of cosmic radiation ranged from about 8% at sea level to about 6% at 2.5 km altitude. Comparable estimates of the CVs for the *neutron* component ranged from about 25% to 5% (Bouville and Lowder 1988). The relative contribution of the neutron component to the total cosmic dose rate ranged from 8% at sea level, to 29% at 2.5 km altitude. In a related study, Bagshaw (2000) estimated that the uncertainty in the estimate of effective dose for the neutron component ranged from 30-50%. This higher estimate was attributed to a lack of knowledge about the complexity of the radiation fields and the response of detectors to the various types of radiations they contain. Similar estimates were reported by the NCRP (1987a), and UNSCEAR (2000). The NCRP estimates accounted for the contributions from the neutron component, variations in the dose rates with latitude and the solar cycle, plus other factors. For purposes of this paper, the overall CV in the dose rate estimates for cosmic radiation was assumed to be 10% for all altitudes.

Published reports include a range of different estimates for the structural shielding factor for cosmic radiation. Studies in the Netherlands, for example, indicated that this factor had a normal distribution, with a mean value of 0.6 (Vaas 1991). While related studies in the United States also led investigators to conclude that this factor had a normal distribution, the mean value was estimated to be 0.8 (NCRP 1987b). Based on the latter value, it is logical to conclude that the total error (at 3 SD) is 20%. Following this approach, the structural shielding factor (at 1 SD) would be 0.8 ± 7%. Although this is important to consider in assessing the total uncertainty, it did not prove, as noted above, to have a significant impact on the dose estimates. Propagating the errors, including a 10% error associated with the estimated dose rate, 7% for the structural shielding, and 7% for the occupancy factors, yields a CV of 14% (i.e., $[(10\%)^2 + (7\%)^2 + (7\%)^2]^{0.5}$) (Table 6). On this basis, the estimated prorated *indoor* plus *outdoor* cosmic radiation dose rates for residents of the Amargosa Valley, yields a value of 0.33 ± 0.05 mSv y^{-1} (Table 5).

Terrestrial radiation

The NCRP (1987a) noted that ground based surveys in four countries, including the United States, showed a normal distribution in measured values of terrestrial radiation, with 95% of the measurements being within 50% of the mean (NCRP 1987a). On this basis, there is only 1 chance in 20 (5%) that the measured value would be more than 2 SD of its normal distribution. In addition, analyses of data from a long-term environmental gamma radiation monitoring program yielded an estimated ±10% variation in the recorded dose rates (Ramsdale and Oduko 1992). In a related U.S, study, Miller (1992) concluded that (a) the mean indoor radiation dose rates were lower than those outdoors by 20%, (b) the ratio of the terrestrial dose rates, indoors vs. outdoors, was 0.59 ± 7% (SD = 0.04). Applying this approach, the estimated prorated *outdoor* terrestrial dose rate for the Amargosa Valley was 0.11 mSy y^{-1} ± 10%. The comparable *indoor* terrestrial dose rate was:

$$0.36 \text{ mSv y}^{-1} \pm [(10\%)^2 + (7\%)^2 + (7\%)^2]^{0.5} = 0.36 \text{ mSv y}^{-1} \pm 14\%.$$

On this basis, the *indoor* terrestrial dose rate was 0.36 ± 0.05 mSv y^{-1} and the total terrestrial dose rate for the Amargosa Valley was:

$$(0.11 \pm 0.01 \text{ mSv y}^{-1}) + (0.36 \pm 0.05 \text{ mSv y}^{-1}) = 0.47 \pm 0.05 \text{ mSv y}^{-1}.$$

Radon and radon decay products

Because of the complexity and relatively large number of factors that must be considered, the estimated dose rates, due to exposures to radon and its decay products, clearly dominated as the largest contributor to the dose rates and their associated uncertainties. These uncertainties are due to a variety of factors. While the concentrations of ^{222}Rn in the air depend to a large extent on the amounts of uranium and ^{226}Ra in the soil, they are also significantly influenced by factors, such as the soil gas pressure which, in turn, depends on the soil radon diffusion coefficient, and the soil to air permeability. The last factor is strongly dependent on the amount of moisture in the soil, and the extent of ground snow cover. The concentrations of radon inside homes depend on the pressure gradient, or "driving force," that enhances its movement into the home. Also important is the condition (porosity) of the floors in the building. Other factors of importance include those related not only to the measurements of the radon concentrations, but also to the breathing rate of the exposed population group; the fraction of the decay products that are not attached to airborne particles, including the influence of dynamic processes, such as enhanced air circulation (i.e. the use of ceiling fans); the status of the radon decay product equilibrium; and the assumptions incorporated into quantifying the dose conversion factor. Uncertainties associated with the last factor include the assumed site of deposition of the decay products; the value of the radiation weighting factor assigned to the alpha particles; and the value of the tissue weighting factor assigned to the bronchial epithelium.

As would be anticipated, numerous studies have been conducted in seeking to quantify the contributions of these various factors to radon dose rate estimates. For example, James et al. (1988) have evaluated the significance of the impacts of the disequilibrium of the radon decay products, and their degree of attachment. In so doing, they recognized that, in most cases, it is possible either to measure, or to have good representative estimates of, the unattached fraction of ^{210}Po, the status of the disequilibrium of the decay products, the associated particle sizes, and the breathing pattern of the exposed population. Based on these observations, they recommended that, for more than 80% of the environmental radon measurements, a dose conversion factor of 1 mSv y^{-1} (20 Bq $m^{-3})^{-1}$ be applied. This same dose conversion factor has been adopted for computing radon dose estimates in Europe (Green et al 1992). In the latter case, the authors estimated that the associated error was ± 50%. While the ICRP (1993) did not recommend the use of the dosimetric approach for assessing radon exposures, some of the questions related to this approach appear to have been resolved by the observation (discussed earlier) that the lung cancer risk in uranium miners is now higher than previously estimated. The ICRP (1993) had previously estimated that the non-statistical uncertainty, based on epidemiological studies, was a factor of two (i.e., 100%). The radon dose rate conversion factor, D, has been uniformly applied in estimating the radon dose rates in this paper. While the uncertainty in the value of the dose conversion factor has a significant impact on the uncertainty analyses, it would not affect the comparisons of the total dose rate estimates.

Another series of studies addressed the role, in terms of uncertainties, of the method used in collecting the radon decay product sample. Georoge and Tu (1988) compared various sampling methods, including the type of equipment used and the interpretation of the collected data. The largest source of error was determined to be the accuracy of the required low-volume air-sampling rate, and the accompanying limitations on the sampling equipment that can be used. The average uncertainty ranged from 16% to 21%, depending on the sampling and/or monitoring device being used (Mellander and Enflo 1992; Smith et al. 1992). Nonetheless, the performance ratios were found to yield a Working Level (WL) ranging from 0.91 to 1.08, with an average of 0.99. On this basis, it will be assumed that the SD associated with sampling and measurement errors was ± 0.1. Smith et al. also reported that the radon concentration can vary appreciably from one locality to the next. In fact, it can vary from one house to another by a factor of 10 to 100 as random error. Taking all these factors into consideration, it appears to be reasonable to assume that the total error associated with radon measurements could be ~100%.

Under these circumstances, statistical testing of the differences in the dose rates for each of the four locations, would require a detailed assessment not only of the measured values of the radon concentrations, but also of the values of the accompanying input factors enumerated above. This would need to be done on a site-specific basis. These considerations, coupled with the fact that Leadville, CO, and the Amargosa Valley, NV, were smaller in geographical area, compared with the States of Colorado and the State of Nevada, was one of the reasons that the difference in the estimated dose rates for these four locations, were emphasized in this paper.

Table 5. Summary of estimated dose rates from natural background sources.

Natural background source	Amargosa Valley, NV	Leadville, CO	State of Colorado	State of Nevada
	Effective dose rate (mSv y^{-1})			
Cosmic radiation	0.33	0.85	0.50	0.39
Terrestrial radiation	0.47	0.97	0.45	0.22
Radon and its decay products	0.54	3.61	3.01	1.74
Total (± 1SD)	1.34 ± 0.13	5.43 ± 1.14	3.96 ± 2.28	2.35 ± 0.94

Overall uncertainty

Summarized in Table 6 are the coefficients of variance for most of the input parameters associated with each of the dose estimates presented in this paper. Even though there were voids in the data, sufficient information was available to quantify the errors in the dose rate estimates in a reasonably acceptable manner. For residents of the

Amargosa Valley, the estimated CV for the dose rates from cosmic and terrestrial radiation was 14%. The CV associated with the radon dose rates using local specific data was 18%, [i.e., $(15\%)^2 + (10\%)^2]^{0.5}$ where the 10% represents the measurement error.

Following this approach, the total dose rate estimate for residents of the Amargosa Valley, NV (AN), applying location specific data and incorporating all propagated uncertainties for exposures to cosmic, terrestrial, and radon sources, respectively, was:

$$\begin{aligned}\Sigma_{AN}\,[\text{mSv y}^{-1}] &= (0.33 \pm 14\%) + (0.47 \pm 14\%) + (0.54 \pm 18\%) \\ &= (0.33 \pm 0.046) + (0.47 \pm 0.066) + (0.54 \pm 0.10) \\ &= 1.34 \pm [(0.046)^2 + (0.066)^2 + (0.10)^2]^{0.5} \\ &= 1.34 \pm 0.13 \text{ mSv y}^{-1}\end{aligned}$$

In a similar manner, the total dose rate estimate for Leadville, CO (LC), was:

$$\begin{aligned}\Sigma_{LC}\,[\text{mSv y}^{-1}] &= (0.85 \pm 14\%) + (0.97 \pm 20\%) + (3.61 \pm 31\%) \\ &= (0.85 \pm 0.012) + (0.97 \pm 0.19) + (3.61 \pm 1.12) \\ &= 5.43 \pm [(0.012)^2 + (0.19)^2 + (1.12)^2]^{0.5} \\ &= 5.43 \pm 1.14 \text{ mSv y}^{-1}.\end{aligned}$$

Similarly, the total dose rate estimate for State of Colorado (CO) was:

$$\begin{aligned}\Sigma_{CO}\,[\text{mSv y}^{-1}] &= (0.50 \pm 14\%) + (0.45 \pm 20\%) + (3.01 \pm 76\%) \\ &= (0.50 \pm 0.07) + (0.45 \pm 0.09) + (3.01 \pm 2.28) \\ &= 3.96 \pm [(0.07)^2 + (0.09)^2 + (2.28)^2]^{0.5} \\ &= 3.96 \pm 2.28 \text{ mSv y}^{-1}.\end{aligned}$$

And finally, the total dose rate estimate for State of Nevada (NV) was:

$$\begin{aligned}\Sigma_{NV}\,[\text{mSv y}^{-1}] &= (0.39 \pm 14\%) + (0.22 \pm 14\%) + (1.74 \pm 54\%) \\ &= (0.39 \pm 0.055) + (0.22 \pm 0.031) + (1.74 \pm 0.94)\end{aligned}$$

$$= 2.35 \pm [(0.055)^2 + (0.031)^2 + (0.94)^2]^{0.5}$$

$$= 2.35 \pm 0.94 \text{ mSv y}^{-1}.$$

Again, as may be noted from these examples, the contributions of the uncertainties associated with the cosmic and terrestrial dose rate estimates are minimal in comparison with those for radon. The availability of site-specific data from the LBNL databank on indoor radon concentrations played an important role in reducing the associated errors in the dose rate estimates and, particularly, the benefits of analyses based on smaller geographic areas. While the coefficient of variance (CV) in the radon dose estimate for the Amargosa Valley was 18%, and that for Leadville, CO, was 31%, those for the States of Nevada and Colorado were 54% and 76%, respectively. Otherwise, the total propagated error for the radon dose rates alone would have been as high as 142%, i.e., $[(100\%)^2 + (100\%)^2 + (10\%)^2]^{0.5}$. For this reason alone, there will be a significant overlap in the distributions of the dose estimates for all four locations.

Table 6. Uncertainty in the input parameters for estimating the dose rates from various sources of natural background radiation.

Natural background source	Sources of uncertainty	Distribution	Estimated CV[(a)]
Cosmic radiation	Derived from equations for estimating dose rates as a function of altitude (0-2.5 km)	Exponential	10%
	Reduction factor for structural shielding of the roof	Normal	7%
	Indoor and outdoor occupancy factors	Discrete	7%
	Thickness and density of the snow cover	Normal	30%[(b)]
	Radiation weighting factor for neutrons (Sv Gy^{-1})	Discrete	30-50%[(b)]
Terrestrial radiation	Dose rate measurements	Normal	10%
	Reduction factor for structural shielding of the floor	Normal	7%
	Indoor and outdoor occupancy factors	Discrete	7%
Radon and its decay products	Sampling and concentration distribution	Lognormal	Site-specific
	Measurement error	Normal	10%
	Dose conversion factor (based on dosimetric and epidemiological considerations)	Lognormal	100%[(b)]
	OVERALL UNCERTAINTY		150%[(c)]

(a) The coefficient of variance (CV) equals the standard deviation divided by the mean.

(b) Data were not used for error propagation.

(c) Most of the uncertainty was contributed by the dose rate from radon and its decay products.

CONCLUSIONS AND COMMENTARY

The primary objective of this review and evaluation was to provide independently developed, scientifically based, information on estimates of the dose rates due to external sources of cosmic and terrestrial radiation, and the inhalation of radon and its decay products, to residents of the Amargosa Valley, NV, and Leadville, CO, and to the populations of the States of Colorado and Nevada. The residents of Leadville, CO, were included the analyses because they reside in an area that is known to have unusually high dose rates from both cosmic and terrestrial radiation, as well as from indoor airborne radon and its decay products. Leadville is also located in a geographic portion of the United States relatively close to the Amargosa Valley, and its population is similar in size.

To avoid having these analyses lead to an overestimation of the difference in the dose rates in the two communities, special care was taken in the case of Leadville not knowingly to select input factors that would lead to a higher total dose rate than justified. Comparable care was taken in the case of the Amargosa Valley not to select input factors that would lead to a lower total dose rate than justified. Examples of the application of this approach, in the case of Leadville, include accounting for reductions in the estimated cosmic and terrestrial dose rates due to the shielding effects of snow. Another conservatism was not to include any potential increase in the winter concentrations of radon inside the homes due to the potential "driving force" of the ground snow ground outside the houses. This is a potential source of enhanced indoor radon exposures that deserves investigation.

With respect to the Amargosa Valley, another potential source of conservatism, that was not evaluated, was the presence of ceiling fans in the homes. Studies show that such fans can, through increased plate-out of the airborne radon decay products, reduce the accompanying dose rates by a factor of two or more (Hinds et al. 1983). Had data on the use of ceiling fans in the Amargosa Valley been available, this could have increased the difference in the dose rates in that community, as contrasted to those for Leadville, CO.

Comparisons showed that the estimated dose rates in Leadville, the State of Colorado, and the State of Nevada, were higher than those in the Amargosa Valley by 4.09, 2.62, and 1.01 mSv y^{-1}, respectively. The coefficient of variance (CV) in the radon dose estimate for the Amargosa Valley was 18%, for Leadville, CO, 31%, the State of Coloado, 76%, and the State of Nevada, 54%.

Even though the estimated natural background dose rates to residents of Leadville, CO, were relatively high, those for all three of the components of natural background, that were evaluated, were low compared to those for these same sources in other areas of the world. Cosmic radiation dose rates in certain high altitude areas range up to 2.0 mSv y^{-1}, and outdoor terrestrial dose rates of 4.3 mSv y^{-1} have been observed. In a similar manner, some areas have indoor radon concentrations that yield estimated effective dose rates ranging up to 10 mSv y^{-1} (ICRP 1999).

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Footnotes

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